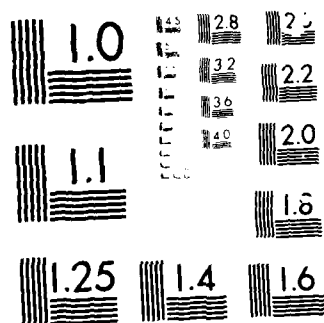


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ABSTRACT

Meteorological Teleconnections Between the Sahel
and the Eastern United States. (December 1985)

Jeffrey Earl Malan, B.G.S., University of Nebraska at Omaha

Chairman of Advisory Committee: Professor John F. Griffiths

The existence of atmospheric teleconnections between the Sahel and the eastern United States is investigated on a seasonal time scale. Precipitation data for the Sahel and surface temperature data for the eastern United States from the years 1951 through 1977 in the months June through October are used. The statistical procedures applied are principal component analysis; Pearson's product-moment and Spearman's rank correlation, simple linear regression. Data of the 700 mb height data are used to produce composite charts of seasonal circulation and for conducting circulation analyses in an effort to associate climate signals with anomalous conditions of the general circulation.

Two readily identifiable modes of large-scale spatial variability are found in the first and second principal components. The first indicates the existence of an inverse relationship between precipitation in the Sahel and surface temperature in the eastern United States. The second principal component indicates a direct relationship between these two regimes. Circulation analyses reveal patterns in the 700 mb height anomaly field which may be connected with the postulated inverse relationship.

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METEOROLOGICAL TELECONNECTIONS BETWEEN THE SAHEL
AND THE EASTERN UNITED STATES

A Thesis
by
JEFFREY EARL MALAN

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December 1985

METEOROLOGICAL TELECONNECTIONS BETWEEN THE SAHEL
AND THE EASTERN UNITED STATES

A Thesis

by

JEFFREY EARL MALAN

Submitted to the Graduate College of
Texas A&M University
in partial fulfillment of the requirement for the degree of
MASTER OF SCIENCE

December 1985

Major Subject: Meteorology

DEDICATION

"To Laura"

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1. INTRODUCTION

a. General

The semi-arid region of sub-Saharan West Africa is referred to loosely in most literature as the Sahel. This region is subjected to considerable seasonal and interannual climate variability which is manifested most significantly as rainfall variability. Rainfall variability in the region over the last three to four decades has been well-documented; below-normal conditions and above normal conditions have tended to last for periods of up to a decade, and have exhibited spatial coherence of regional extent (Nicholson, 1981). A wetter-than-normal period was experienced in the 1950's, while a drier-than-normal period occurred in the late 1960's to the middle 1970's. Rainfall for the years between these periods of anomalous conditions was found to be near-normal throughout the region (Lamb, 1978b).

The socio-economic system of this semi-arid region of Africa is very sensitive to rainfall variability (Glantz, 1977). Under the more optimal rainfall conditions of the 1950's and early 1960's, agriculture and pastoralism expanded northward toward the Sahara. As more land became intensely cultivated the region supported greater numbers of people and animals. When conditions became drier in the late 1960's and early 1970's a crisis developed. The period between 1968 and 1973 was, in fact, one of serious drought. Increased levels of agriculture and larger herds of grazing animals no longer

The citations on the following pages follow the style and format of the Monthly Weather Review.

could be supported, which led to over-grazing and destruction of the land's utility. Widespread famine become prevalent and many people and animals died as a direct result of the drought (Oliver, 1981).

Seasonal and interannual rainfall variability in this region may be attributed to variability of specific features of the atmospheric general circulation. A complete understanding of the various manifestations and of the behavior of these features of course has not yet been acquired, but certainly would help in an understanding of rainfall variability. One possible way of gaining an understanding of the nature of the features of the seasonal atmospheric general circulation which particularly affect the semi-arid region of sub-Saharan West Africa is by correlation of temporal fluctuations in meteorological indicators at locations distant from the region. This kind of correlation is sometimes referred to as a teleconnection (Wallace and Gutzler, 1981). One kind of teleconnection would be the correlation of two disparate meteorological regimes which are both influenced by one particular feature of the atmospheric general circulation. A teleconnection of this type may suggest that some kind of relationship exists between the meteorological regimes. Teleconnection patterns also suggest physical mechanisms may exist.

b. Objectives

The primary objective of this study is to examine a possible relationship on a seasonal time scale between the meteorological regimes of the eastern United States and of the Sahel. This

objective is accomplished by performing the following tasks:

- 1) Development of two sets of meteorological data, one set consisting of surface temperature data for the eastern United States and one set consisting of precipitation data for the Sahel.
- 2) Examination of the two sets of data to identify significant climate signals on the seasonal time scale and the regional spatial scale.
- 3) Correlation of significant climate signals identified from each of the two sets of data.
- 4) Review of temporal and spatial variations of features of the seasonal atmospheric general circulation over the North Atlantic Ocean and its continental environs.
- 5) Association of significant climate signals from (2) and (3) above with anomalous conditions of particular features of the general circulation.

c. Background

The eastern United States is a region in the temperate latitudes, influenced by the Atlantic-maritime air mass. The western side of the North Atlantic subtropical high pressure system affects this meteorological regime, particularly from the late spring through early autumn months. Hotter-than-normal conditions during these months generally can be attributed to the persistence or recurrence of a pronounced extension of the subtropical high pressure system over the eastern United States (Erickson, 1983). Cooler-than-normal conditions, on the

other hand, may be attributed to above-average cyclonic activity and subsequent cloud cover in concurrence with a weaker, less-pronounced extension of the high pressure system (Madden and Williams, 1978).

The Sahel lies in subtropical latitudes and is also influenced by the Atlantic-maritime air mass (see Figures 1 and 2). The eastern side of the North Atlantic subtropical high pressure system affects this meteorological regime. The region is affected seasonally by the South Atlantic subtropical high in addition to the high in the Northern Hemisphere. The Intertropical Convergence Zone (ITCZ) can be identified as a dividing zone between air masses associated with these two features (Griffiths, 1972). The seasonal excursion of all these features southward is characterized by a dry season in the Sahel which occurs from late autumn through early spring (November through May). The northward excursion of the features is characterized by a wet season which occurs from late spring through early autumn (June through October).

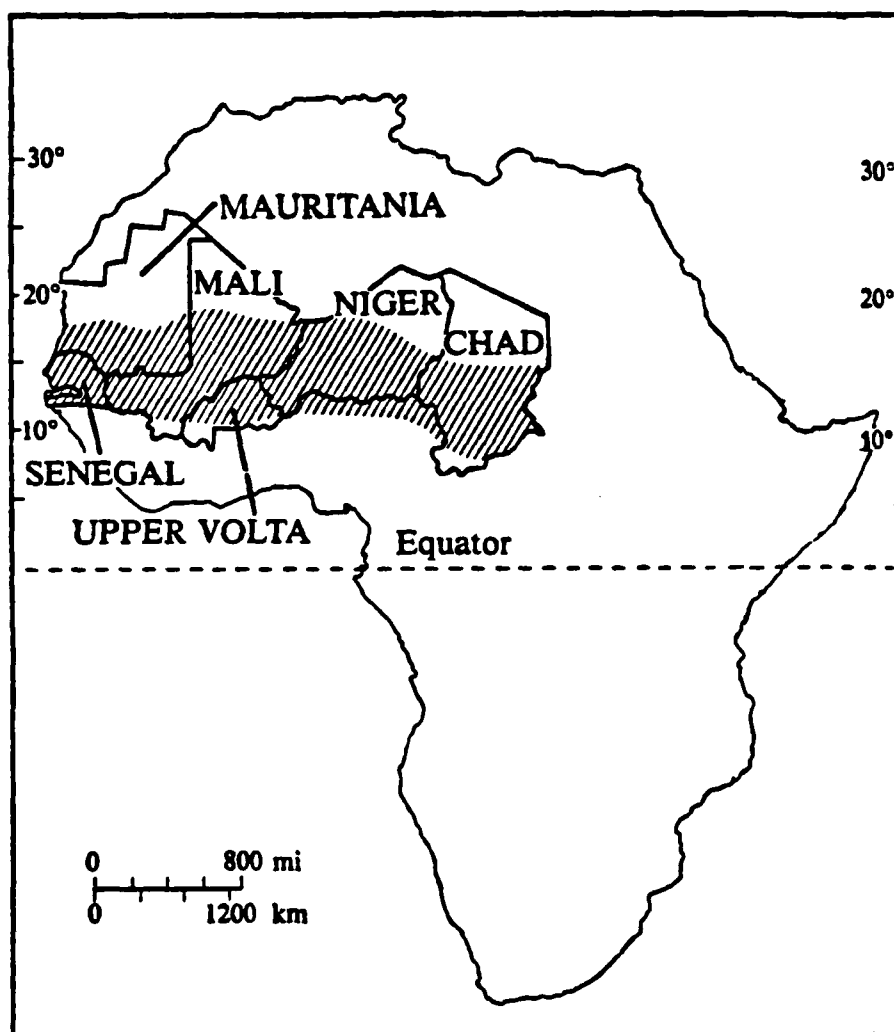


Fig. 1. The geographical region of West Africa referred to as the Sahel. The Sahel is the shaded area.

2. LITERATURE REVIEW

The concept of meteorological teleconnections may be described in several ways. It can be described broadly as a statistical/physical correlation between two, or among more than two, atmospheric circulations or "centers of action," or among indicators of these, such as pressure, temperature or precipitation. The concern is with a correlation of temporal fluctuations of these features.

The idea of the existence of centers of action, or macro-scale pressure patterns, and their relationship to prevailing weather conditions was first presented by Teisserenc de Bort (1883). Later, Hildebransson (1897) demonstrated that correlations between weather conditions over one region of the globe and those over another distant region could be found. Significant contributions were made to this idea of correlation between weather conditions at distant locations by Sir Gilbert Walker [Walker (1923, 1924); Walker and Bliss (1932)]. In his series of research papers Walker provides evidence of three large teleconnection patterns in which an inverse relationship exists between pressure in one region and pressure in another. These patterns are:

- 1) The North Atlantic Oscillation (NAO), involving the Icelandic low and the Azores high pressure area.
- 2) The North Pacific Oscillation (NPO), involving the Aleutian low and the North Pacific high pressure area.
- 3) The Southern Oscillation (SO), involving pressure over the South Pacific Ocean and over the equatorial Indian Ocean.

Rossby (1939) later formulated a theory for the behavior of the centers of action, and this work provided some explanation for the teleconnections specified by the other researchers.

The research cited above formed a foundation for later work, much of which has been devoted to the SO phenomenon. The SO exhibits a zonal, east-west teleconnection pattern manifested as a global-scale fluctuation primarily reflecting a shift of mass between the Indonesian equatorial low pressure cell and the South Pacific subtropical high pressure cell (Walker and Bliss, 1932; Troup, 1965). The NAO exhibits a mostly meridional teleconnection pattern which is evidenced by an inverse relationship between sea level pressure in the vicinity of the Icelandic Low and a broad east-west belt centered on about 40°N which extends from the western North Atlantic to the Mediterranean (Walker and Bliss, 1932). An analogue to the NAO pattern proposed by Walker and Bliss is the NPO pattern which shows a north-south seesaw in sea level pressure between a high-latitude belt extending from eastern Siberia to western Canada and a broad low-latitude belt including the subtropics and extending northward to near 40°N. Dickson and Namias (1976) proposed another teleconnection pattern labeled by some as the Pacific/North American (PNA) pattern (Wallace and Gutzler, 1981) which also has somewhat of a combined zonal and meridional nature. It can be seen in the mid-tropospheric geopotential height field, extending from the mid-Pacific Ocean to eastern North America and is characterized by an alternation between a blocking pattern and a more zonally oriented flow pattern.

Recent research by Wallace and Gutzler (1981) has disclosed some

other teleconnection patterns; among these are an Eastern Atlantic (EA) pattern and a Western Atlantic (WA) pattern, both of which appear to be related to the NAO pattern. These patterns appear dominant at mid-tropospheric levels. Barnett (1981) conducted research on meteorological teleconnections which was concerned not only with the identification of spatial patterns, but also with the implications of them. He investigated interactions of anomalies of fields of both sea level pressure and sea surface temperature in the Pacific Ocean with aspects of the meteorological regime over North America. His results suggested a teleconnection in the climate system from the equatorial regions of the Pacific Ocean to higher latitudes.

Erickson (1983) also examined the possibility of relationships between teleconnection patterns and weather conditions. Erickson's research involved anomalies of both sea level pressure and 700 mb height related to mean summer temperatures in the United States. His findings revealed an association of unusually warm summers with a three-cell pattern of anticyclonic anomalies over the eastern North Pacific, the United States and the North Atlantic; also noted were mostly above-normal heights for the entire Northern Hemisphere north of 15°N, but especially at subtropical and lower middle latitudes. Generally, for unusually cool summers opposite patterns were found. Erickson also computed lag correlations between zonally averaged 700 mb height anomalies and United States mean summer temperatures, and these suggested a very broad and large-scale relation.

Namias (1972) suggested the association of large-scale features of the atmospheric general circulation, particularly the North Atlantic

subtropical high, with aspects of the meteorological regime in north-east Brazil. The hypothesis proposed was that the northeast trades are frequently regulated by the Atlantic subtropical anticyclone which in turn is regulated by the upstream westerly long-wave activity. Variations of these features alter the intensity of convergence into the ITCZ, and perhaps change its position so that variable demands may be placed on the southeast trade wind system affecting the moisture influx from the South Atlantic. In other research Namias (1974) proposed an association of 700 mb heights over higher latitudes of Europe and the North Atlantic with precipitation conditions in the Sahel region of Africa. He found that dry conditions at Dakar, Senegal and Niamey, Niger corresponded with high 700 mb heights over northern latitudes of Europe and the North Atlantic; also, these dry conditions corresponded with low heights over southern latitudes of the North Atlantic, east Africa and the Mediterranean.

Namias (1974) also made suggestions for research into the role of teleconnections in understanding tropical climate fluctuations, particularly fluctuations of interannual rainfall in the region of the African Sahel. According to Namias, the first procedure should be to specify the features of the general circulation which are associated with excess or deficient rainfall for selected stations or groups of stations. Another procedure is to obtain a reasonably long-period record of rainfall and a file of reasonably good upper air data over distant areas, such as Europe, the Mediterranean and the Atlantic.

A number of explanations have been proposed for such rainfall fluctuations in the Sahel. Bryson and Murray (1977) attributed the

conditions of the rainy season in the Sahel to a meridional displacement of the large-scale features, such as the mid-tropospheric prevailing westerlies, anticyclone deserts, the intertropical discontinuity (ITD) and moist monsoon air; a northward displacement corresponding with wet conditions and a southward displacement corresponding with dry conditions. Lamb (1978a,b) postulated that several features of the general circulation, such as the Tropical Atlantic near-equatorial trough, the kinematic axis and the zone of maximum sea surface temperatures, may be located farther to the north or south of their usual positions during an anomalously wet or an anomalously dry rainy season, respectively. Nicholson (1981) proposed that a northward shift of the general circulation features may be responsible primarily for wetter-than-normal years, but that the occurrence of drier-than-normal conditions may be related to the intensity of the rainy season as governed by other factors. Miles and Follard (1974) found a trend for several features, such as the subtropical pressure maximum and the maximum of the westerlies, to shift northward while rainfall was on the decline. Tanaka et al. (1975) suggested that changes in the morphology of certain features, such as the subtropical high pressure belt and the trough of the mid-latitude westerlies, rather than the variation of latitudinal excursion of them, may be related to rainfall production during the rainy season. Bunting et al. (1975) suggested that a predictor of rainfall in the region may be the variation of a 700 mb geopotential anomaly located over the Sahel.

Among the features of the general circulation mentioned above which may be important in the course of resolving meteorological

teleconnections, and for determining rainfall conditions associated with such teleconnections that may affect the Sahel, is the North Atlantic subtropical high pressure system. This feature is mentioned by Miles and Follard (1974) and by Tanaka et al. (1975). Given that the North Atlantic subtropical high is an important feature in this regard, then a reasonable expectation is that anomalous conditions of it and of precipitation in the Sahel may exist simultaneously. Given also that this subtropical high is a feature which has relevance to large-scale temperature regime in the United States (Trewartha, 1968; Erickson, 1983), another expectation is that anomalous conditions of the feature and of surface temperature in the particular part of the United States that is most directly exposed to the subtropical high pressure system, namely the eastern region, may also exist simultaneously. Since teleconnection patterns may infer relationships between meteorological regimes, and because they may suggest physical mechanisms, a reasonable proposal is that a correlation may exist between two regimes, such as those in the Sahel and in the eastern United States, which are both influenced by a particular salient feature of the general circulation, such as the North Atlantic subtropical high. This study is concerned with investigating such a correlation, or teleconnection.

3. DATA

Surface temperature is used in this study as an indicator of the character of features of the seasonal atmospheric general circulation over the eastern United States. During the period of late spring through early autumn, surface temperature is a reasonably reliable indicator on a regional scale of the character of the normal and anomalous meteorological regimes manifested, for example, as the strength, position and persistence of the subtropical high pressure system. A network of stations in the United States has been established so as to give an acceptable representation of the large-scale temperature pattern over approximately the eastern one-third of the country. The chosen stations are evenly spaced throughout the region. The density of stations in the region was not of primary concern; however, consideration was given such that a network of sufficient density be used to determine as strong and as coherent a climate signal as possible. Temperature data have been obtained for each month from June through October of the years from 1951 through 1977 from Local Climatological Data, Annual 1977 (NOAA). Table 1a lists the 15 stations of record from which temperature data have been taken. No data are missing from these stations' records. Figure 3a is of a map of station locations in the eastern United States.

Precipitation is used as an indicator of features of the seasonal circulation over the Sahel. The rainy season is defined as the period from June through October. Whereas temperature in this region is a somewhat less-sensitive element to climate fluctuations (Griffiths,

Table 1a. Stations in the eastern United States.

Lakeland, Florida	Wilmington, Delaware
Mobile, Alabama	Pittsburgh, Pennsylvania
Macon, Georgia	Detroit, Michigan
Memphis, Tennessee	Madison, Wisconsin
Greensboro, North Carolina	Worcester, Massachusetts
Lexington, Kentucky	Albany, New York
Springfield, Illinois	Portland, Maine
	Caribou, Maine

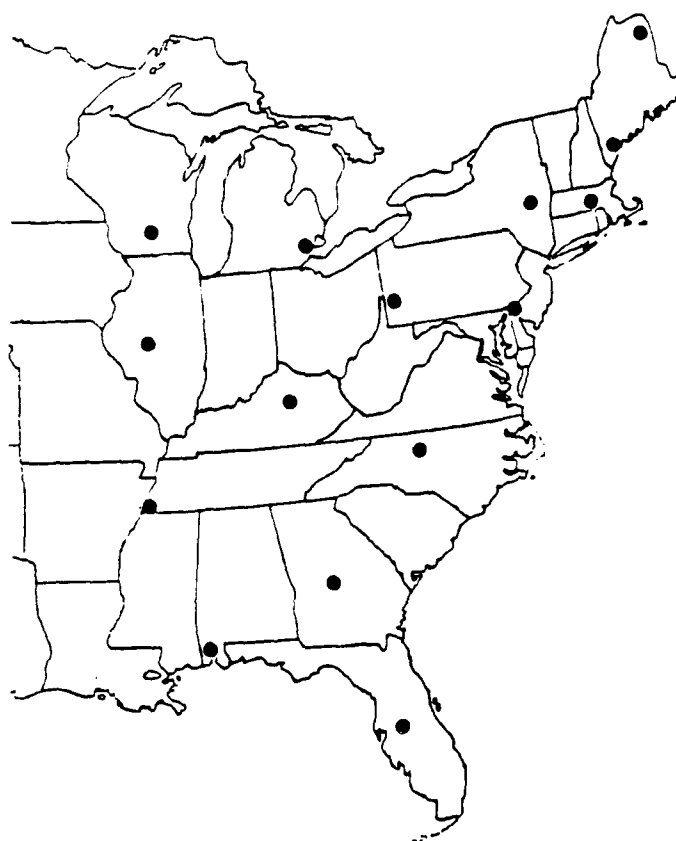


Fig. 3a. Regional distribution of stations in the eastern United States.

1972), rainfall is more representative of the character of the region's normal and anomalous meteorological regimes. A network of stations has been established in order to give a representation of precipitation pattern of a geographical region bounded by 18°N , 10°N , by the Atlantic Ocean (approximately 18°W) and by approximately 5°E . The number of stations in the region which recorded and disseminated meteorological measurements consistently and from the same location is relatively small. Therefore, using as great a number of stations as possible was of greater concern than spacing or density. Precipitation data have been obtained also for each month from June through October from World Weather Records, Volume 5 (ESSA) of the years from 1951 through 1960, and from Monthly Climatic Data for the World (NOAA) of the years from 1961 through 1977. Table 1b lists the 18 stations of record from which precipitation data were taken. Stations with excessive amounts of missing data were not used. Some data are missing from the records of those stations which have been used. Missing data have been replaced with the appropriate monthly means as computed from available monthly values within the period of the data base covering the years from 1951 through 1977. Figure 3b is of a map of station locations in the Sahel.

700 mb height data for use in constructing composite charts of time-averaged (seasonal) circulation and for conducting circulation analyses have been extracted from data sets compiled by Namias (1979), these also for the years from 1951 through 1977. These data sets exist in a seasonal format such that data are already time-averaged according to the conventional four seasons of the year; thus, the summer season

Table 1b. Stations in the Sahel.

Dakar, Senegal	Nioro du Sahel, Mali
Linguere, Senegal	San, Mali
St. Louis, Senegal	Segou, Mali
Tambacounda, Senegal	Sikasso, Mali
Zinguinchor, Senegal	Bobo Dioulasso, Upper Volta
Gao, Mali	Boromo, Upper Volta
Hombori, Mali	Dori, Upper Volta
Menaka, Mali	Fada N'Gourma, Upper Volta
Mopti, Mali	Kandi, Benin

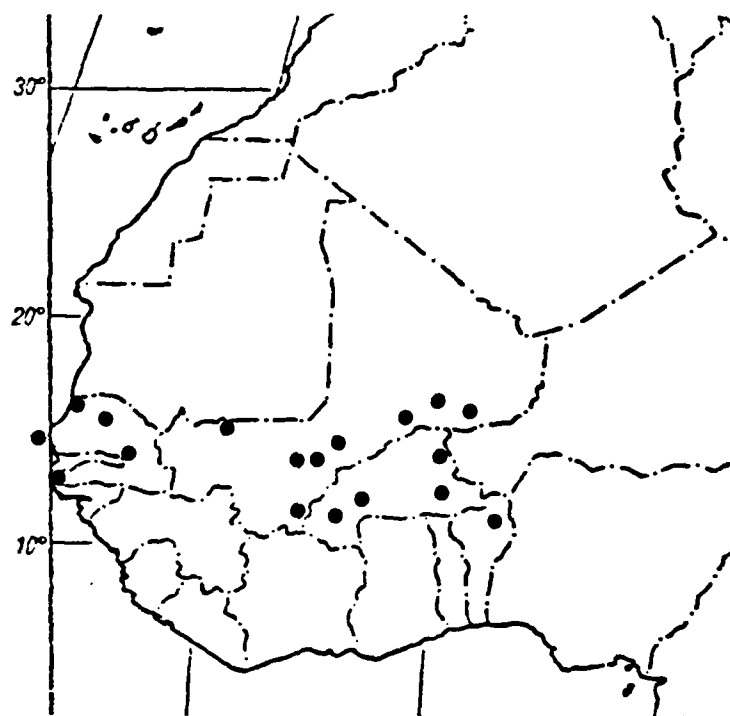


Fig. 3b. Regional distribution of stations in the Sahel.

for which charts have been constructed is the June-July-August period. A grid-point network of the data covers an area bounded by 50°N, 20°N, 90°W and the Equator which includes the eastern United States, western Europe, northwest Africa and a large expanse of the Atlantic Ocean. The grid points are located at intersections of a 10 degree-square grid, thus height values exist for a total of 40 grid points in the area of interest.

4. METHODS OF ANALYSIS

a. Data development

Two basic sets of meteorological data, one for the eastern United States and one for the Sahel, have been developed for use in subsequent statistical analyses. The two sets have been developed for the 27-year period from 1951 through 1977. Means of temperature for the period from June through October were computed from monthly means for each station in the eastern United States for each year of the 27-year period. Sums of precipitation for the same period of months were computed from monthly totals for each station in the Sahel, also for each year.

Out of the total of 27 years of data from the eastern United States and from the Sahel a random sample of 15 years has been taken. Means for the Sahel region were computed from the seasonal (June through October) sums of precipitation for each station for each year, and were ranked and grouped into terciles before the random selection process was begun, thus making the sample a stratified random sample. The random selection process was accomplished by randomly picking five years of each tercile category (low, intermediate, high) of mean precipitation for a total of 15 years. Subsequently, the 12 years of data remaining have been used for a control.

b. Principal component analysis

Principal component analysis has been employed to isolate

simultaneous broadscale patterns of meteorological regime of temperature in the eastern United States and of precipitation in the Sahel, and to resolve climate signals from these patterns. The output statistics of such an analysis are principal components, eigenvalues and eigenvectors. The principal components (a_i) represent linear combinations of the number (p) of random variables X_1, X_2, \dots, X_p . The eigenvalues (λ_i) are equal to the variances of the principal components, and provide a convenient measure of the relative importance of each component. Eigenvectors describe the spatial pattern, and eigenvector coefficients (e_{ij}) are measures of the importance of each variable to the i -th principal component. In a sense, the eigenvector coefficients can be likened to regression coefficients. Thus, the i -th principal component is given vectorially by

$$a_i = [e_{1i}X_1, e_{2i}X_2, \dots, e_{pi}X_p]$$

Principal component analysis have been found to be useful in its application to the study of interrelationships between fields of several kinds of meteorological variables in the time domain. Kutzbach (1967, 1970) concluded that principal component analysis could be applied in descriptive or diagnostic studies in which these interrelationships between fields of variables are not clearly understood. Kidson (1975) resolved that, by employing principal component analysis, a comparatively small number of climatological indices could represent gross features of the general circulation. While the advantages may be evident, some short-comings and limitations are inherent in this method. Nicholson (1980) advised that one inherent limitation of principal

component analysis is that modes of variation are, according to theory, statistically independent, or orthogonal. Nicholson suggested that because actual climatic variation is not characterized by this orthogonality, the application of a correlation method may be better suited to such studies of interrelationships between fields of meteorological variables.

c. Correlation

Two methods of correlation have been employed to examine the degree of statistical relationship between prominent climate signals as indicated by the simultaneous broadscale patterns of meteorological regime in the eastern United States and in the Sahel suggested by the eigenvectors of the principal component analysis. The two methods are Spearman's rank correlation and Pearson's product-moment correlation. The purposes served by these aspects of association analysis are that they measure the strength of the relationship among the sample observations, and that they provide a point estimate of the strength of the relationship between the variables in the population. They also provide a basis for testing the significance of the point estimate of the strength of the relationship between the variables in the population.

Pearson's product-moment correlation provides a measure of the strength of a linear relationship between variables. The product-moment correlation coefficient is non-dimensional. The correlation coefficient is usually designated as r , and its definition is given by

$$r = \frac{\sum_{i=1}^p (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^p (x_i - \bar{x})^2 \sum_{i=1}^p (y_i - \bar{y})^2}}$$

where X and Y are the variables of interest (temperature and precipitation), and \bar{X} and \bar{Y} their respective means. The Pearson product-moment correlation coefficient has the following characteristics:

1) When r is positive a direct relationship is indicated, 2) when r is negative an inverse relationship is indicated and 3) when r is equal to or near to zero the variables are not linearly related. A perfect direct relationship is said to exist when $r = +1$, and a perfect inverse relationship exists when $r = -1$. As was previously stated, the Pearson product-moment correlation coefficient permits conclusions as to the existence of a linear relationship between two variables, but does not indicate which variable causes the variation of the other.

Spearman's rank correlation also provides a measure of the strength of a relationship between variables, but strictly speaking, it is a measure of that strength of relationship between the ranks of the sample observations, rather than between the observations themselves. Further, the relationship may be other than linear. For data consisting of observations from a bivariate population the pairs of observations are designated (X_1, Y_1) , (X_2, Y_2) , ..., (X_p, Y_p) . Here the correlation coefficient is designated as r_s , and its definition is given by

$$r_s = \frac{\sum_{i=1}^p (R_i - \bar{R})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^p (R_i - \bar{R})^2 \sum_{i=1}^p (S_i - \bar{S})^2}}$$

where R and S are the ranks of the variables X and Y , respectively, and \bar{R} and \bar{S} are the means of the ranks, R and S . If ties occur among the X 's or among the Y 's, the mean of the rank position for which any value is tied is used. As with the product-moment correlation coefficient, when a perfect direct relationship exists $r_s = +1$, and when a perfect inverse relationship exists $r_s = -1$. In the former case the rank of X is the same as the rank of Y for every pair of observations, whereas in the latter case the rank of one variable within each pair of observations is the reverse of the other. Given that rank correlation yields a non-parametric measure of relationship, the exact measure of strength that r_s is estimating and the statistical significance of r_s are more difficult to interpret compared to product-moment correlation. Further, in the case of rank correlation a bivariate normal distribution need not be assumed.

Nicholson (1980) proposed that correlation methods may be generally suitable for approaching the problem of climatic variation, while Ramage (1983) cautions against placing an abundance of trust in correlation coefficients, particularly when physical connections cannot be made. Application of standard statistical theory to correlation coefficients which are derived from correlation analysis of meteorological variables may, in fact, lead to incorrect conclusions for the

following reasons: 1) a permanent relationship between variables may not exist for the population; 2) due to interdependence of data, the degrees of freedom may be difficult to assess; 3) correlation exists randomly, even in random data.

d. Regression

Simple linear regression has been used to obtain a linear mathematical equation that describes the functional relationship between the variables, given that a linear relationship may be indicated by the product-moment correlation analysis. In regression analysis designation of one variable as the independent variable and of the other variable as the dependent or response variable is customary. Usually, changes in the independent variable are accompanied by coincident changes in the response variable. How the dependent variable changes as a result of a change in the independent variable is an indication of the effect of the independent variable on the response. This effect is given mathematically by the regression function.

The form of the model for simple linear regression is given by

$$Y = \beta_0 + \beta_1 X + \epsilon$$

where X is the independent variable, Y is the response variable, β_0 is the intercept of the regression line, β_1 is a regression coefficient which is the slope of the regression line, and ϵ denotes the random experimental error. Using the method of least squares, the estimates b_0 and b_1 are found for β_0 and β_1 , respectively:

$$b_1 = \frac{\sum_{i=1}^p (X_i - \bar{X})(Y_i - \bar{Y})}{\sum_{i=1}^p (X_i - \bar{X})^2} ,$$

$$b_0 = \bar{Y} - b_1 \bar{X} .$$

Using the estimates b_0 and b_1 in the regression equation leads to the estimated regression equation

$$\hat{Y} = b_0 + b_1 X .$$

Some limitations which are inherent in this form of analysis are the same as some of those pertaining to correlation analysis. Additionally, that a change in one variable causes a change in another may not necessarily be inferred just because a function has been found that is a good fit to a set of observed data. A regression model which describes such a function may still prove useful, however, as an analytic and possible predictive tool.

e. Seasonal circulation analysis

Seasonal circulation analyses have been accomplished to facilitate identification of features or patterns of seasonal circulation corresponding to anomalous and average conditions of precipitation in the Sahel. The procedure used is one in which composite maps are constructed by averaging a height field for cases of selected meteorological/climatological conditions, such as years of low, intermediate or

high category of precipitation. The procedure is suitable given that variations of one basic type of pattern are primarily responsible, or assumed to be responsible, for the conditions under study.

5. RESULTS

a. Selection of a random sample

The distribution of the years of the 15-year sample and of the 12-year sample among the three tercile categories are shown in Tables 2a and 2b, respectively. Generally, what the table shows is consistent with the presumption that the decade of the 1950's was one of relatively abundant rainfall (high category). The intermediate category is comprised mostly of the years of the 1960's, and the low category is comprised mostly of the years of the 1970's. Out of the whole 27-year period only two of the nine years from the 1950's decade are not included in the high tercile category, and only one of those two years falls into the low category; only one of the eight years from the 1970's is not included in the low category; only two of the ten years of the 1960's decade are not of the intermediate category.

b. Identification of climate signals

Principal component analysis was performed on the 15-year sample of both eastern United States surface temperature and Sahel precipitation. The developed sets of data first were ranked and grouped into terciles within the 15-year sample, treating the set for each region individually. The ranking and grouping process made use of each station's seasonal mean temperature in one set or of each station's seasonal precipitation total in the other, ranking each year with respect to every other year. The purpose of grouping here was to filter out some of the small-scale spatial variability which is regarded as noise and which may not be

Table 2a. Distribution of years of seasonal precipitation means of the 15-year sample among the tercile categories.

Low	Intermediate	High
1968	1960	1951
1970	1961	1953
1971	1963	1954
1973	1965	1964
1974	1966	1967

Table 2b. Distribution of years of seasonal precipitation means of the 12-year independent control sample among the tercile categories.

Low	Intermediate	High
1959	1956	1952
1972	1962	1955
1976	1969	1957
1977	1975	1958

directly caused by general circulation features.

Results of the principal component analysis indicate some larger-scale modes of spatial variability among many small-scale modes. Figure 4 shows that the proportion of the variance which is accounted for by the first principal component is about 32%, and the second principal component accounts for about 21%. The third principal component accounts for about 10% of the variance, and the remaining principal components account for smaller and smaller proportions of the total variance. Added together, the first three principal components account for well over half of the total variance. The graph (Fig. 4) shows that plotted points exist for only the first 14 principal components (the eigenvalue which corresponds to the 15th principal component is zero), even though the total number of principal components should be 33 (this corresponds to the total number of stations: 15 in the eastern United States, 18 in the Sahel). Eigenvalues exist for only the first 14 principal components because the number of variables (stations) used in the analysis is greater than the number of observations. Thus, the analysis problem is underspecified. An important consideration which is relevant to an interpretation of these results is that some uncertainty has been introduced due to this underspecification problem. The number of dimensions which result are limited, thus some sampling fluctuations are inherent in the analysis. These fluctuations are largest in the eigenfunctions of the smaller eigenvalues; these eigenfunctions are not used in this study.

The results which pertain to the eigenvectors are interesting. Most notably, the first eigenvector of the principal component analysis

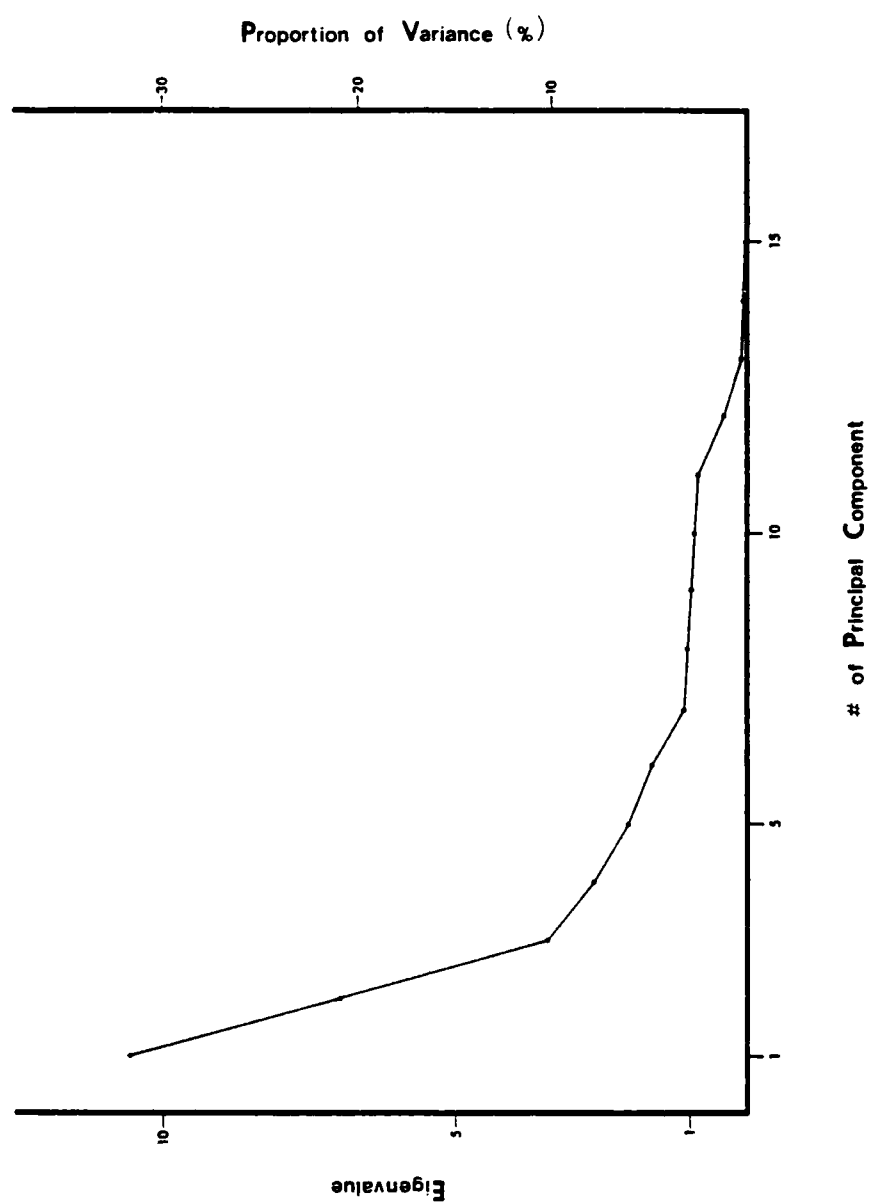


Fig. 4. Graph of eigenvalues and corresponding proportions of variance vs. principal components. The results of that part of the principal component analysis shown here indicate some larger-scale modes of spatial variability among many small-scale modes. Plotted points exist for only the first 14 principal components due to underspecification of the analysis problem.

produced coefficients for the variables corresponding to the Sahel stations which are of the opposite sign of those corresponding to the eastern United States. These results can be seen in Table 3. This kind of high-low (positive-negative) pattern is normally found in the second eigenvector, rather than in the first in principal component analysis of geophysical data. Of the Sahel stations, three have relatively low coefficient values compared to the other values for the region, while about four or five values are relatively high.¹ Of United States stations, two have relatively low values compared to the other values for that region, while about six values are relatively high. Of the six stations in the United States region which have high coefficient values five are located in the northeastern quadrant of the region. The general interpretation of the first eigenvector leads to an inference of a spatial mode of variability whereby an inverse relationship exists between surface temperature in the eastern United States and precipitation in the Sahel.

The second eigenvector produced coefficients which are nearly all of the same sign for both regions. These results can also be seen in Table 3. The case in which nearly all variable coefficients are of one sign is normally found in the first eigenvector, rather than in the second, in principal component analysis of geophysical data. Only two stations, one in the Sahel region and one in the eastern United States region, differ in sign from the rest. The coefficient values of these two are relatively low. Thus, a direct relationship seems to

¹When interpreting the contribution each station makes to any particular eigenvector, the absolute value of the coefficient is used.

Table 3. Eigenvector coefficients of the first five eigenvectors (total number of eigenvectors is 33). The first and second eigenvectors indicate relationships between the Sahel and the eastern United States, whereas the remainder of the eigenvectors indicate relationships which may exist on a smaller, sub-regional scale, or on an intra-regional basis

	1st	2nd	3rd	4th	5th
Dakar	0.229909	0.080219	0.037865	0.190062	0.245891
Linguere	0.140857	0.089913	0.399251	0.139402	-.056506
St. Louis	0.245453	0.104939	-.020017	0.081899	0.188638
Tambacounda	0.072282	-.046068	-.380927	-.256556	0.233243
Zinguinchor	0.161041	0.020661	0.121004	0.214572	0.439973
Gao	0.135814	0.273946	-.065208	0.075316	-.185298
Hombori	0.154091	0.151122	0.182665	0.113649	0.030072
Menaka	0.150444	0.195643	-.162127	0.331628	-.048333
Mopi	0.129718	0.031312	0.323579	-.094133	0.075530
Nioro du Sahel	0.257401	0.134182	-.111805	0.004288	0.097794
San	0.191163	0.221317	-.142009	-.016704	0.104991
Seguo	0.238004	0.089062	0.026400	-.098476	0.253510
Sikasso	0.135324	0.244605	0.216892	0.027574	-.205962
Bobo Dioulasso	0.110945	0.210809	0.110622	-.012273	-.314837
Boromo	0.142226	0.133582	0.093729	-.271610	-.016884
Dori	0.097354	0.101957	-.313235	0.145258	0.198152
Fada N. Gourma	0.068932	0.183518	-.252661	0.218910	-.313919
Kandi	0.202327	0.110437	-.017821	-.100975	-.231891
Lakeland	-.028210	0.148256	-.037058	-.196424	-.197304
Mobile	-.183970	0.165556	0.062151	-.246298	0.227804
Macon	-.168133	0.260874	0.073296	-.113520	-.006532
Memphis	-.149285	0.265116	0.033807	-.167061	0.141112
Greensboro	-.087784	0.234288	0.257299	-.209064	0.141899
Lexington	-.141163	0.310308	0.022079	-.046874	0.026521
Springfield	-.146932	0.258948	-.202086	0.023571	-.011108
Wilmington	-.238475	0.105333	0.107312	-.075886	0.051547
Pittsburgh	-.172941	0.271529	-.062202	0.120545	0.096201
Detroit	-.245703	0.059758	-.159545	-.044376	0.039873
Madison	-.146932	0.258948	-.202086	0.023571	-.011108
Worcester	-.201810	0.083119	-.009484	0.217967	0.132224
Albany	-.204096	0.079288	0.175879	0.307724	0.141124
Portland	-.239144	0.031355	0.093770	0.211473	0.041340
Caribou	-.214612	-.076688	0.077045	0.364475	-.082255

be inferred between eastern United States temperature regime and Sahel precipitation regime by interpretation of the second eigenvector.

An interpretation of results pertaining to the third eigenvector (Table 3) does not lead readily to an inference of any kind of relationship between the two regions of interest. Perhaps some sub-regional or intra-regional relationships are suggested, but these are not of concern here.

The results pertaining to the fourth and fifth eigenvectors which are also shown in Table 3 and the results of the rest of the eigenvectors which are not shown also are apparently not meaningful in terms of relationships between meteorological regimes of the eastern United States and the Sahel.

c. Correlation of climate signals

Correlation analyses were performed, using Spearman's rank correlation method first. This analysis was performed using stations which exhibited the largest contribution to the particular mode of spatial variability (eigenvector) as suggested by the results of the principal component analysis. Such stations were chosen according to an arbitrary criterion based on absolute values of eigenvector coefficients. A threshold for coefficient values was established so as to collect the stations with the highest values for use in the analysis. Stations having coefficient values $\geq |0.20|$ thus were used in this correlation analysis, and in the subsequent product-moment correlation analysis.

Considering the coefficients produced in the first eigenvector, five African stations met the threshold criterion: Dakar, Saint Louis,

Nioro du Sahel, Segou and Kandi. Six United States stations met the threshold criterion: Wilmington, Detroit, Worcester, Albany, Portland and Caribou. A correlation coefficient was calculated using these stations to determine the degree of the inverse relationship inferred by the first eigenvector. A mean precipitation amount for each year of the 15-year sample period was computed using values of the five African stations and a mean temperature value for each year of the same period was computed using values of the six United States stations. Both means then were used to represent their respective regions in the actual calculation of the correlation coefficient, r_s . Thus, the degree of the inverse relationship as suggested by the first eigenvector and as measured by Spearman's rank correlation coefficient is given as $r_s = -0.58$. A significance test of this value of r_s indicates that it is significant at the 0.05 significance level as determined from a table of critical values of r_s , the Spearman test statistic. The precise meaning of this significance test, and of those following, is uncertain due to the circumstances of the selection procedure which employed the threshold criterion as described above. Principal component analysis extracts the most highly correlated pattern, even from a sample of random data; the random distribution, against which the current results are to be tested, is actually unknown. Thus, although the present result is intriguing, ($r_s = -0.58$) the estimated confidence level is in question.

In the second eigenvector, four African stations met the threshold criterion: Gao, San, Sikasso and Bobo Dioulasso. Seven United States stations met the criterion: Macon, Memphis, Greensboro, Lexington,

Springfield, Pittsburgh and Madison. A rank correlation coefficient was calculated using regional means computed from these stations in the same manner as before. The degree of the direct relationship as indicated by the second eigenvector and as determined by Spearman's rank correlation coefficient is given as $r_s = +0.37$. A test of this value of r_s , using the same table as before, reveals that it is not significant at the 0.05 level.

Pearson's product-moment correlation analysis was employed after doing Spearman's rank correlation analysis. The same arbitrary threshold criterion was set for collecting stations to be used in the actual calculation of product-moment correlation coefficients. Once again working with information given in the first eigenvector, and of course, using values of the same five African stations and the same six United States stations as were used in the calculation of the rank correlation coefficient, a product-moment correlation coefficient was calculated. The degree of an inverse linear relationship, then, is given as the result of that calculation: $r = -0.69$. This is a higher coefficient than that obtained using the rank correlation method. A significance test indicates that this value of r is significant at the 0.01 level.

The calculation of a product-moment correlation coefficient for the relationship indicated by the second eigenvector was performed, again using values of the same four African stations and of the same seven United States stations as were used in the rank correlation analysis of this indicated relationship. The extent to which a direct linear relationship exists as indicated by the product-moment

correlation coefficient thus is given as $r = +0.19$. The value of this coefficient is considerably lower than the rank correlation coefficient which was calculated to measure the same kind of relationship. As would be expected then, a significance test indicates that this value is not significant at the 0.05 level, nor is it even significant at the 0.10 level.

Given that the above analyses may indicate the existence of an inverse relationship between surface temperature in the eastern United States and precipitation in the Sahel for the complete seasonal period of June through October, without a time lag, the next step was concerned with breaking the whole period up into sub-periods of two and three months for purposes of determining correlations of the same relationship with time lags. The lag product-moment correlations were performed using values of the five African stations and of the six United States stations collected for correlation analysis in the first eigenvector (above). The same 15-year data period was involved, as well. A mean of precipitation was computed for each month of the June-through-October period from precipitation amounts for each of the five African stations: a mean of temperature was computed in the same manner from temperature values for each of the six United States stations.

The first lag correlation analysis was performed using means of June-July temperature and of August-September-October precipitation. The strength of this proposed lag correlation as indicated by the product-moment correlation coefficient is given as $r = -0.28$ which is not significant at either the 0.05 or the 0.10 levels. The result of a second lag correlation analysis using means of June-July-August

temperature and of September-October precipitation is given as $r = -0.32$. This second value also is not significant at levels of 0.05 or 0.10.

The final procedure was to examine the strength of the suggested inverse relationship for the seasonal period on a month-to-month basis. Correlation coefficients were computed for each month of the period June through October. The monthly mean values of precipitation and of temperature, computed as described above for use in lag correlation analyses, thus were employed for this procedure. The results of the procedure are shown in Table 4. What this breakdown shows is that August is clearly the month during which the postulated inverse relationship is strongest. Values of the product-moment correlation coefficients increase in the negative sense as August is approached in time, and the values decrease in the negative sense as time goes forward from the month of August.

Perhaps a relevant fact to consider here is that August is the middle month of the July-August-September period which is considered to be the wettest quarter of the year in the Sahel (Griffiths, 1972); further, what is observed in this study is that August is very often the month during which the most precipitation is measured. The numbers shown in Table 4 may correspond to changes in size, shape, strength or orientation of the subtropical high pressure system, or they may correspond to the nature of the seasonal excursion of it and other features of the general circulation. The numbers could be interpreted to indicate that a shifting of such features may occur, such that corresponding changes in the relationship between surface

Table 4. Month-to-month product-moment correlation coefficients for the period of June through October of the 15-year sample.

	June	July	August	September	October
June	+0.25				
July		-0.26			
August			-0.68		
September				-0.16	
October					+0.08

temperature in the eastern United States and precipitation in the Sahel occur. Oliver (1981) proposed that a change of only one-third of a degree of latitude in the position of the Atlantic high pressure system is represented by one degree of change in latitude in the position of the ITCZ; such changes in the positions of these features could affect the temporal and spatial distribution of rainfall in the Sahel.

The results may be indicative of a state of the general circulation which develops gradually through the wet season after the month of June, reaches a peak in August, and then diminishes rapidly thereafter. The correlation may be highest in August because the influence of the subtropical high pressure system may be greatest during that time. The feature had been anticipated to have substantial influence also during the months of July and September, however, the numbers do not support this notion.

The fact that August appears to be the only month out of the five months during which the inverse relationship is verified weakens a hypothesis that a physically-based inverse relationship may actually exist. Month-to-month correlation coefficients of September and October show almost no correlation between surface temperature in the eastern United States and precipitation in the Sahel, and an interpretation of these numbers contributes to a general suspicion that, overall, the results may not be highly significant. Further, the radical difference between the correlation coefficients of August and September seems to contradict the idea that changes in the state of general circulation features may be responsible. Changes in the state of general circulation features likely do not occur as rapidly and drastically as the

numbers indicate. The main problem, then, seems to be in attributing the kind of results that were obtained from the month-to-month correlations to possible physical mechanisms of the general circulation. Specifically, the question arises as to what event could happen in the month of August that happens only sporadically, or not at all, in other wet-season months.

d. Regression of a postulated relationship

A linear regression equation was produced to describe the functional inverse relationship as indicated by the first eigenvector and the previous product-moment correlation analysis. Values for the same five African stations and the same six United States stations, all of which have been used in all previous analyses concerning the inverse relationship, were employed here, as well. These values are of the 15-year sample period. The resulting estimated regression equation thus is given as

$$Y = 5482.4 - 138.1X ,$$

where temperature ($^{\circ}\text{C}$) of the eastern United States is the independent variable, and precipitation (mm) of the Sahel is the other response variable. The corresponding line of regression is shown in Figure 5.

Superposed on the graph is a scatter plot of points of both the 15-year random sample (crosses) and the 12-year independent control sample (dots). By inspection, the pattern of the plot of the control points does not conform very well to the line of regression. A product-moment correlation coefficient was calculated for the 12-year

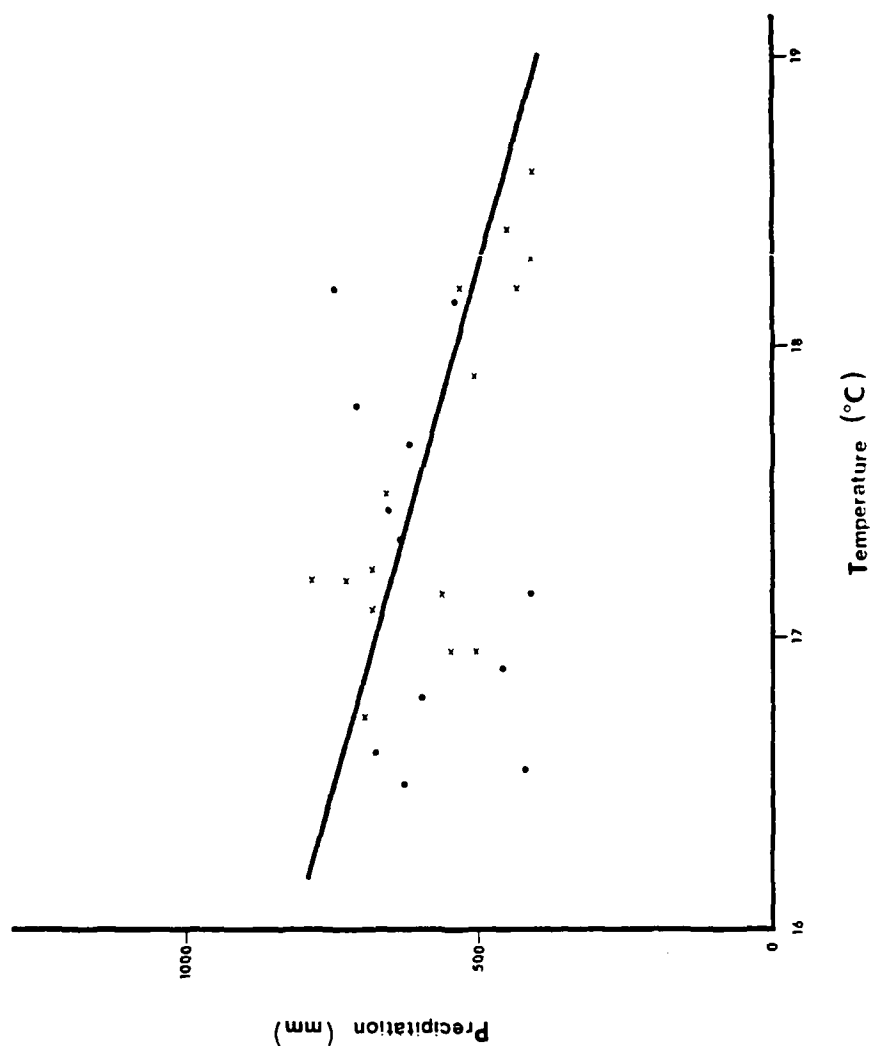


Fig. 5. Sahel precipitation as a function of eastern United States surface temperature. The line of regression is constructed from the regression equation $Y = 5482.4 - 138.1X$ (determined from the 15-year sample). The scatter plot is of both the 15-year sample (crosses) and the 12-year control sample (dots).

control period, again using values for the same five African stations and the same six United States stations as for the 15-year period. The result of the calculation is given as $r = +0.36$. While not significant as the 0.10 level, this result works to the discreditation of the postulated inverse relationship.

Since such a result was obtained from correlation analysis of the 12-year independent control sample, a product-moment correlation coefficient was computed for the entire 27-year period. This result is given as $r = -0.24$. Whereas this correlation coefficient does indicate an inverse relationship, significance tests at both the 0.05 and 0.10 levels do not establish statistical confidence. Apparently, in light of this, whatever signal exists is not strong enough to be verified with only a 27-year sample.

e. Analysis of corresponding states of seasonal circulation

Composite analyses of gridded 700 mb height data were done for the three Sahel precipitation categories (low, intermediate, high).² These analyses are shown in Figures 6, 7, and 8. Data for the entire 27-year period were used, thus each category is comprised of nine seasons/years of data. The distribution of the years among the categories can be seen in Tables 2a and 2b. Additionally, a 27-year mean of the data was computed to be used to compute departures from the mean of the data in each category. The analysis of this 27-year mean is shown in Figure 9.

²

The seasonal data taken from Namias (1979) are in units of feet, rather than in meters. Whereas these units do not inhibit either the analysis of the data or a subsequent interpretation, use of metric units is generally preferred.

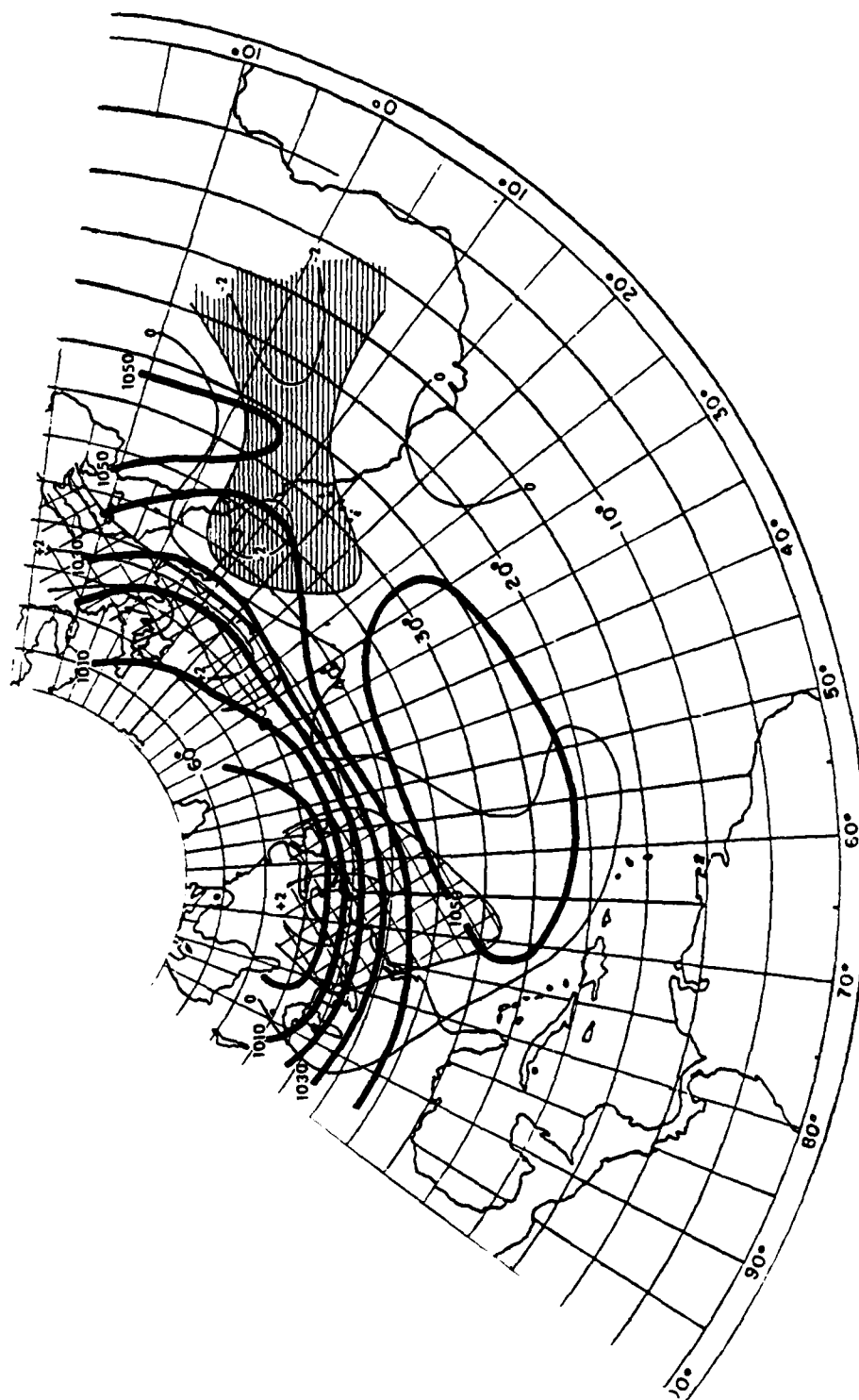


Fig. 6. Low precipitation category composite. 700 mb heights and anomalies are labeled in tens of feet. Areas of positive departures are represented by cross-hatching; areas of negative departures are shaded with horizontal lines.

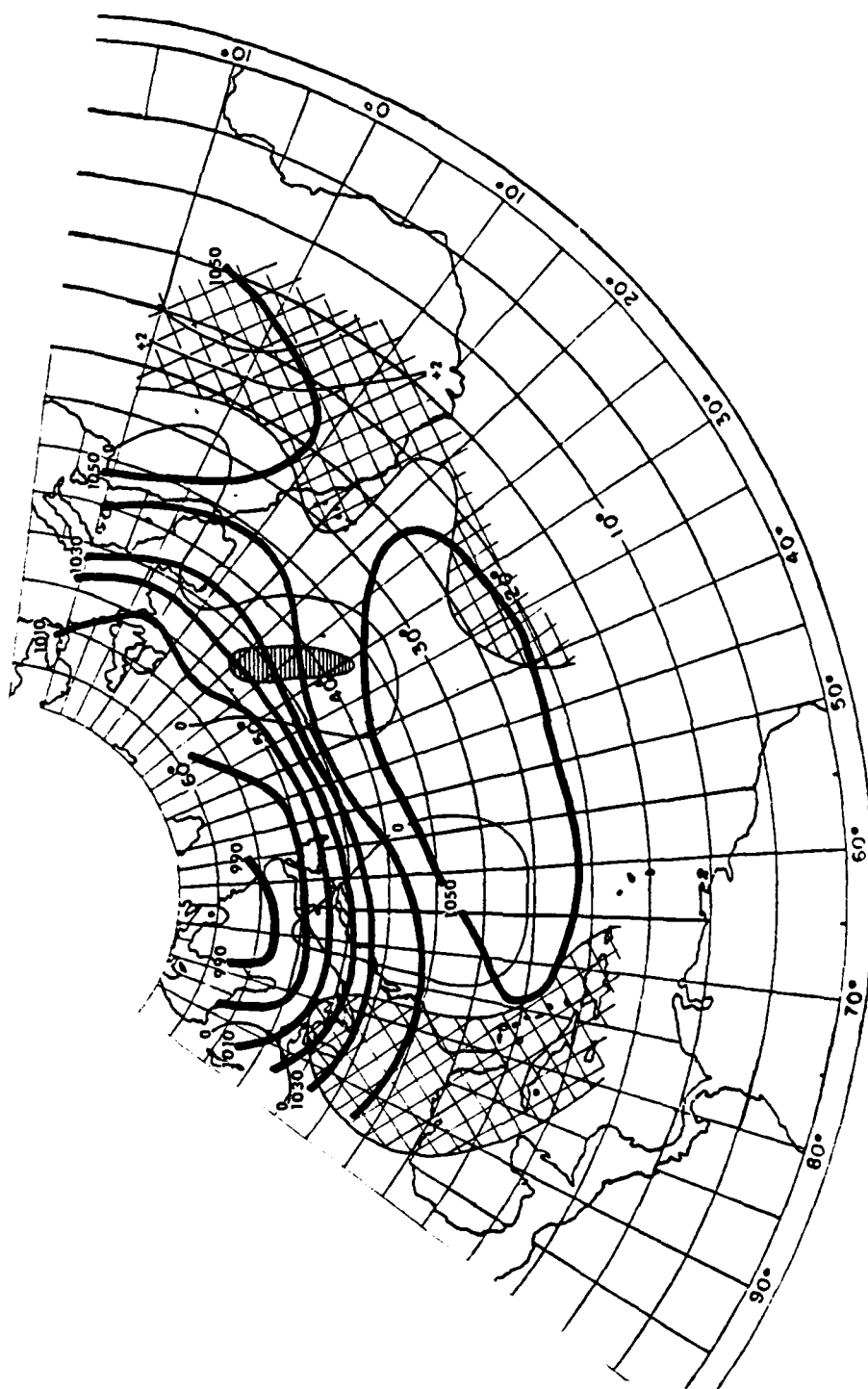


Fig. 7. High precipitation category composite. 700 mb heights and anomalies are labeled in tens of feet. Areas of positive departures are represented by cross-hatching; areas of negative departures are shaded with horizontal lines.

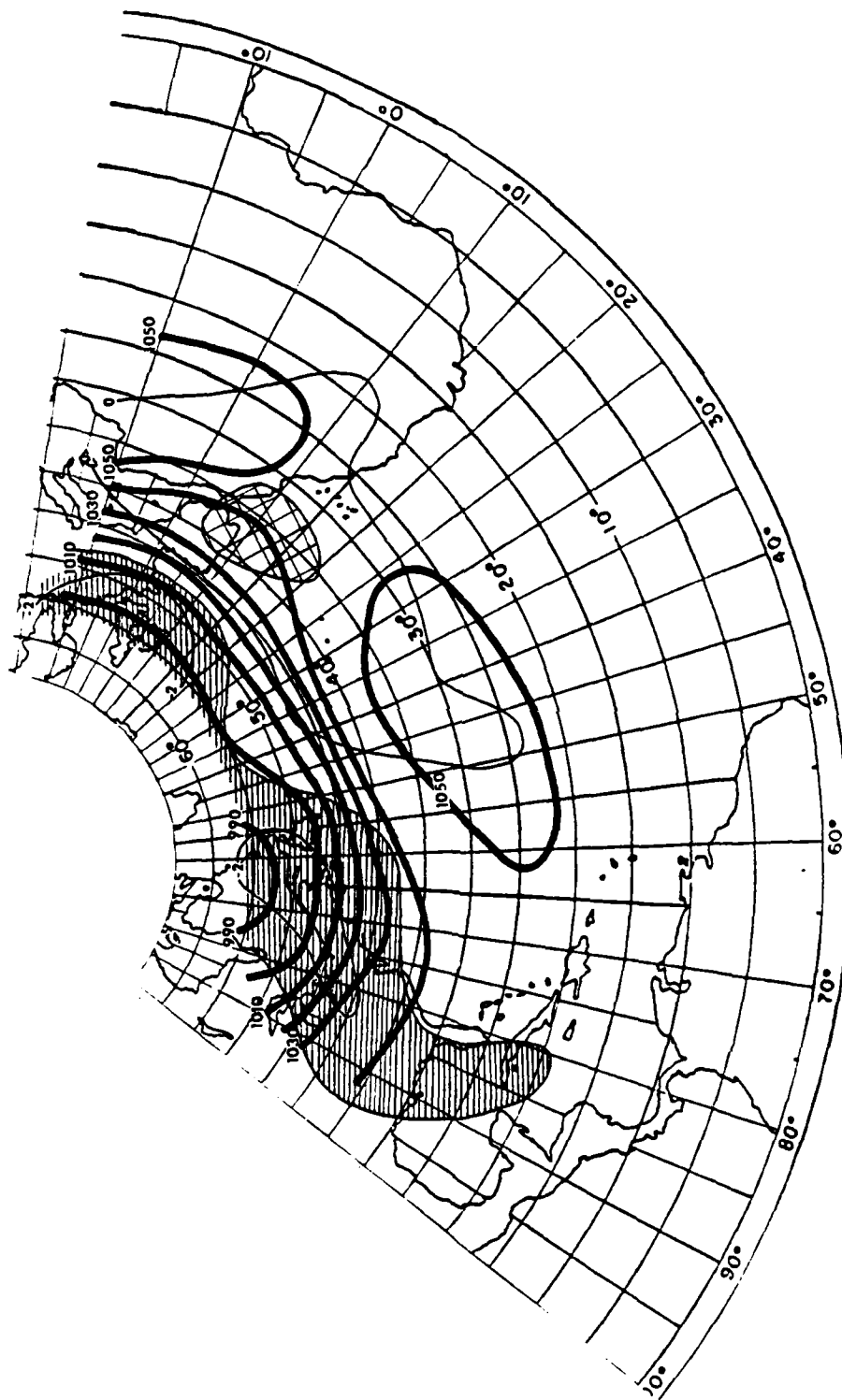


Fig. 8. Intermediate precipitation category composite 700 mb heights and anomalies are labeled in tens of feet. Areas of positive departures are represented by cross-hatching; areas of negative departures are shaded with horizontal lines.

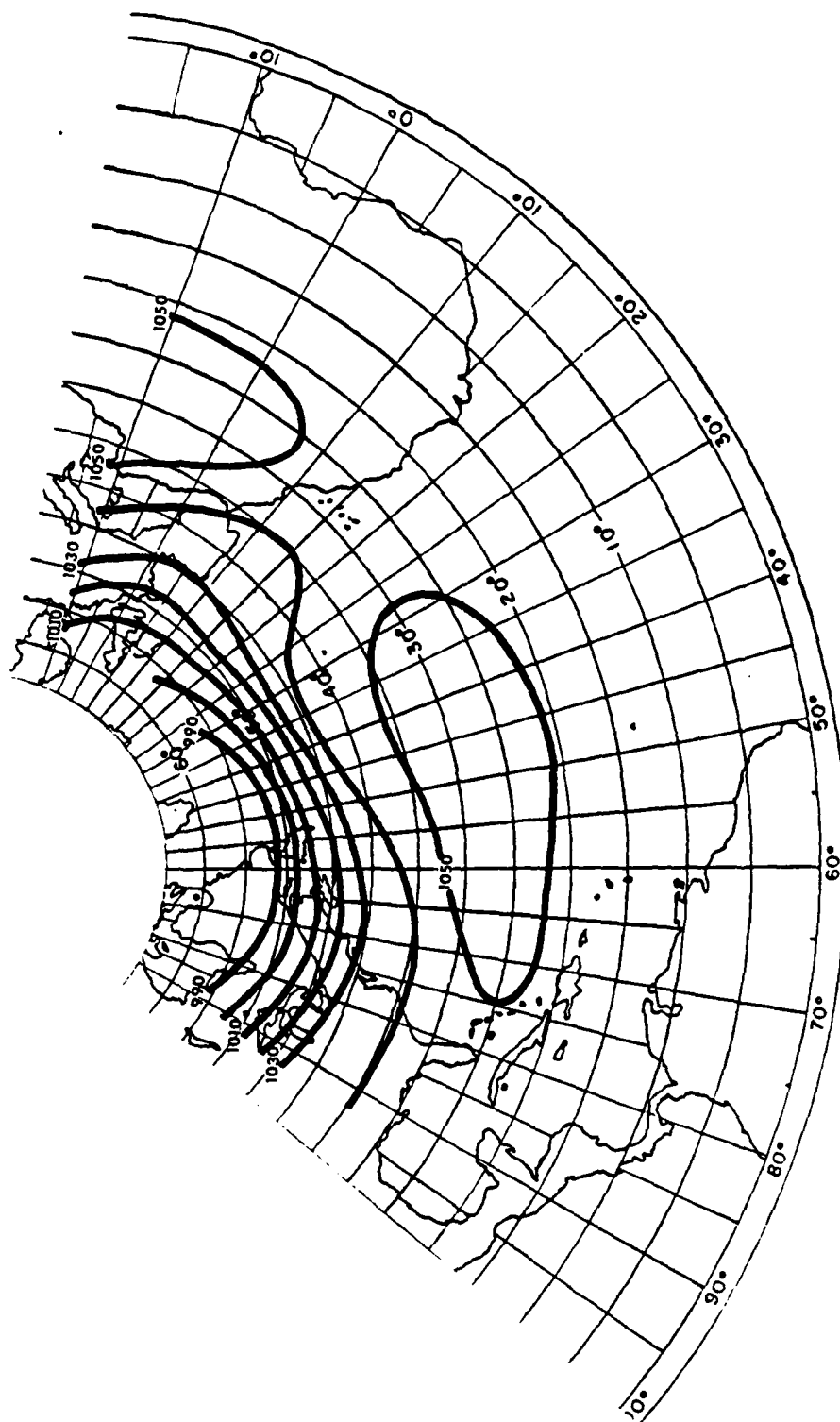


Fig. 9. Mean 700 mb height analysis for the 27-year period (1951-1977).

The departures from the mean facilitated subsequent analyses of height anomalies for the three precipitation categories. The anomaly patterns are superposed on Figures 6,7, and 8.

Generally, the contour patterns of the three composites and the mean appear similar. Major features which are common to all four contour analyses are a trough over the north-eastern United States, a trough near the west coast of Europe, and a large, zonally-oriented ridge (the subtropical high) which extends from the western Atlantic to northern Africa.

The configuration of the trough over the northeastern United States on the low precipitation composite chart varies slightly from the mean chart in that the trough appears a little farther west and appears to have somewhat lesser amplitude than the mean. Also, the low composite chart shows the trough near western Europe to be slightly east of the mean position and to have slightly greater amplitude than that of the mean. In this same case the ridge appears to have greater amplitude to the north over the Atlantic and lesser amplitude to the south over northern Africa, compared to the mean.

The high precipitation composite chart shows that no basic differences are apparent between the appearances of the two troughs during years of high precipitation and their appearances in the case of the mean. The ridge position looks to be about the same as the mean but again differences in amplitude can be seen. Overall, the ridge appears to exert more influence eastward over the Atlantic and southward over northern Africa than in the case of the mean.

A comparison of the intermediate precipitation composite chart to

the mean chart reveals that no decidedly noticeable difference of the characteristics of the troughs is observed between the two charts. The ridge appears not to extend as far westward in the intermediate case compared to the mean, otherwise, no difference is readily apparent in this feature.

The analyzed anomaly patterns of the three composites for the most part support what already has been noted concerning the contour patterns, but these anomaly patterns also help to resolve variations of the features of the contour patterns from the mean more definitively and more clearly. The anomaly pattern of the low precipitation composite chart reveals a conspicuous area of departures above the mean (positive departures) over the northeastern United States, and another area of positive departures over northwestern Europe. Also evident is an elongated area of departures below the mean (negative departures) extending northwestward from northern Africa to an over-water region just off the Iberian peninsula.

The anomaly pattern of the high precipitation composite shows an area of positive departures over all but the north-eastern third or so of the eastern United States. An area of negative departures is shown to be over a northeastern section of the Atlantic and over northwestern Europe. Positive departures are seen over sections of northern Africa.

The composite chart of the intermediate precipitation category shows an area of negative departures which encompasses the entire eastern United States region and northwestern Europe. A small area of positive departures is located just southwest of the Iberian peninsula.

An interpretation of the low precipitation category is that an

eastern extension of the high may have been relatively weak in this case while a western extension may have been somewhat stronger than usual. Under these circumstances the ITCZ could be expected to migrate further north over Africa, and have more influence than usual. Rainfall production thus should have been increased over the Sahel, but low rainfall was observed instead. In the case of the high precipitation category composite an interpretation of what may have happened with the subtropical high is not quite so straightforward. Generally, the high could be expected to have more influence over the Atlantic, particularly over the eastern portion. This contrasts with the low precipitation case. The high heights seen over much of northwestern Africa in this case should have corresponded with an inhibited northward migration of the ITCZ and a decrease in rainfall in the Sahel; however, high rainfall was observed. Another noteworthy item is that the intermediate precipitation composite actually resembles the high precipitation composite.

6. CONCLUDING REMARKS AND RECOMMENDATIONS

a. Concluding remarks

Some evidence has been given which suggests that one possible mode of seasonal climate variation which relates to the North Atlantic subtropical high pressure system and its continental environs is one in which an inverse relationship may exist at times between surface temperature in the eastern United States and precipitation in the Sahel. This relationship was indicated in the first principal component of the principal component analysis, using a 15-year sample taken from the total 27-year period of 1951 through 1977. The relationship was examined, using data from stations which exhibited the largest contribution to the first eigenvector. The data were used to compute two types of correlation coefficients: Spearman's rank correlation coefficient and Pearson's product-moment correlation coefficient. The computed correlation coefficients served to lend support to the relationship while at the same time casting a shadow of doubt over the validity of the relationship in terms of actual physical mechanisms. A linear regression equation was determined, but a scatter diagram showed that plotted points of data from the entire 27-year period were widely scattered around the regression line. This finding prompted the calculation of another product-moment correlation coefficient, using data from the 12-year control sample, which produced a result that weakly indicate a direct relationship, rather than an inverse relationship. Conclusions about the existence of a teleconnection between the Sahel and the eastern United States based on the

statistical results of this study thus are difficult to reach. Samples larger than those used here are needed to either substantiate or refute a statistical relationship such as that suggested in this study.

b. Recommendations

Certainly, the results given in this study fall short of giving any conclusive evidence of a teleconnection which is manifested as an inverse relationship between surface temperature regime in the eastern United States and precipitation regime in the Sahel. Specific recommendations follow which are relevant to a better resolution of this possible meteorological teleconnection.

1) Conduct research using the same or similar procedures which are used in this study, but develop meteorological data sets derived from a data base of a longer period of time. The same problem of obtaining consistent meteorological records will undoubtedly be encountered, no matter whether the period is extended forward or backward in time. Additionally, obtaining a homogeneous data base is likely to be a problem.

2) Perform more correlation analyses, particularly analyses of lag correlation, using numerous other combinations of the months of the seasonal period of June through October, and perhaps using months immediately antecedent to this period. Further correlation analyses may shed more light on the nature of the teleconnection examined here. Promising results of lag correlation analyses would have important implications in terms of a contribution to the long range forecast/

outlook problem.

3) Attempt to obtain gridded data or actual observations for use in composite analyses of points south of 20°N . Southern Hemisphere data would be useful, particularly to examine the influence that the South Atlantic region is important, since it is the primary source of low-level moisture for rainfall production in the Sahel.

4) Perform composite analyses of other pressure surfaces in the middle to lower troposphere and of sea level pressure. Certainly, three-dimensional composite analyses would present a clearer picture of states of the atmosphere, and likely would facilitate a better understanding of those states as associated with a teleconnection between meteorological regimes. Perhaps computer graphic capabilities should be exploited in this endeavor.

5) Perform composite analyses for other time periods, such as a July-August-September period or a July-August-period, or perhaps even for single-month periods. A relevant pattern may be better resolved in this manner.

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VITA

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